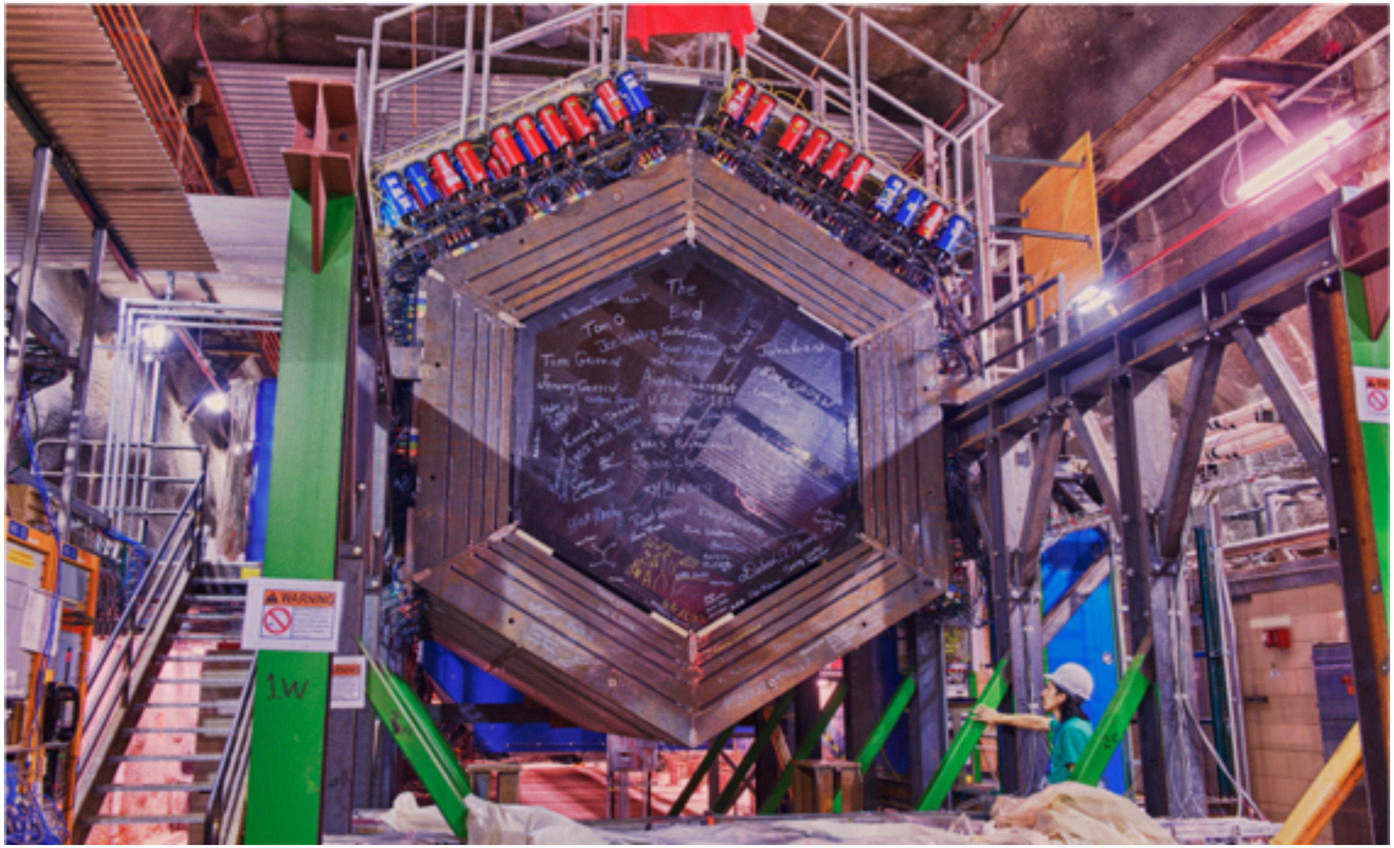


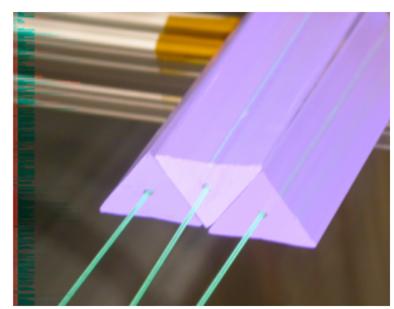
MINERvA in a Nutshell

The MINERvA Collaboration

13 December 2016

MINERvA Overview

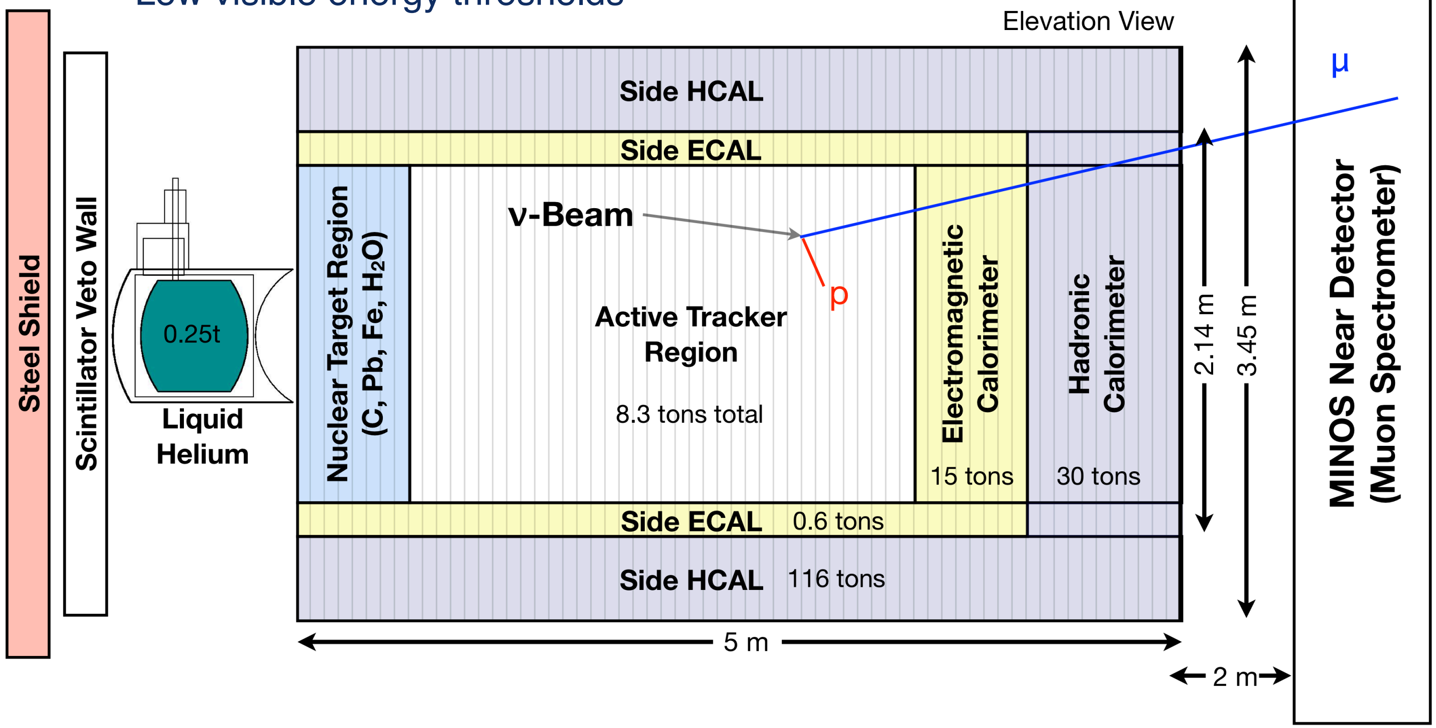
- Scintillator-based detector in on-axis NuMI beam at Fermilab
- Goals Include
  - Inclusive and exclusive measurements of signal and background reactions relevant to oscillation experiments (current and future)
  - Study of nuclear effects via measurements on many nuclei in the same beam
  - Nuclear structure functions



MINERvA Detector

Solid Scintillator (CH) Tracker

- Tracking, particle ID, calorimetric energy measurements
- Low visible energy thresholds



MINOS Near Detector

- Provides muon charge and momentum

Nuclear Targets

- Allows side by side comparisons between different nuclei
- Pure C, Fe, Pb, LHe, water

Side and Downstream Electromagnetic and Hadronic Calorimeters

- Allow for event energy containment

MINERvA Collaboration

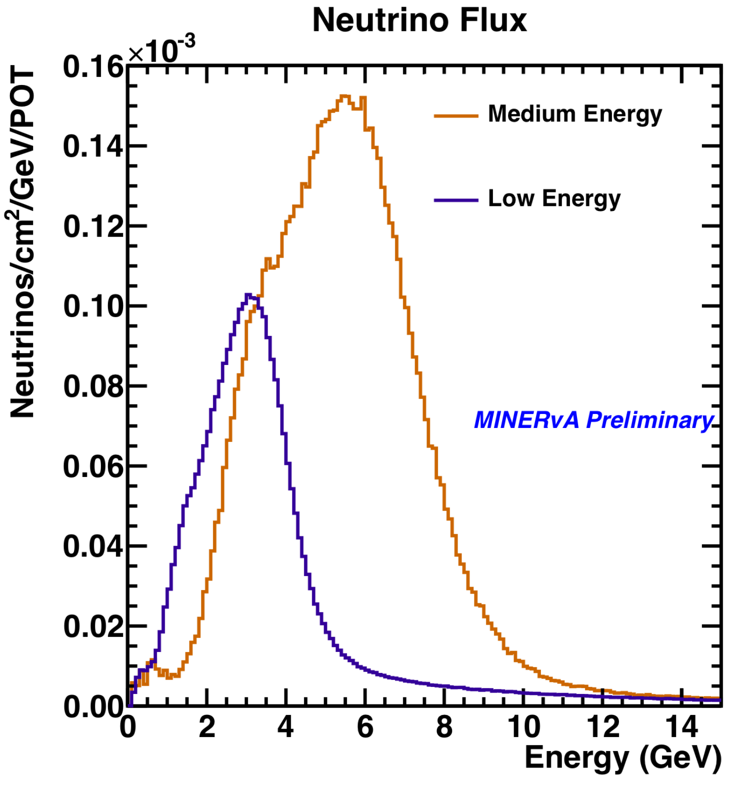
~ 65 Particle, nuclear and theoretical physicists from 21 Institutions:

Aligarh Muslim University
Centro Brasileiro de Pesquisas Fisicas
Fermilab
University of Florida
Universite de Geneva
Universidad de Guanajuato
Hampton University
Massachusetts College of Liberal Arts
University of Minnesota at Duluth
University of Mississippi
Otterbein University

Universidad Nacional de Ingenieria
Potificia Universidad Catolica del Peru
University of Pennsylvania
University of Pittsburgh
University of Rochester
Rutgers, the State University of New Jersey
Universidad Tecnica Federico Santa Maria
Tufts University
College of William and Mary
University of Wroclaw

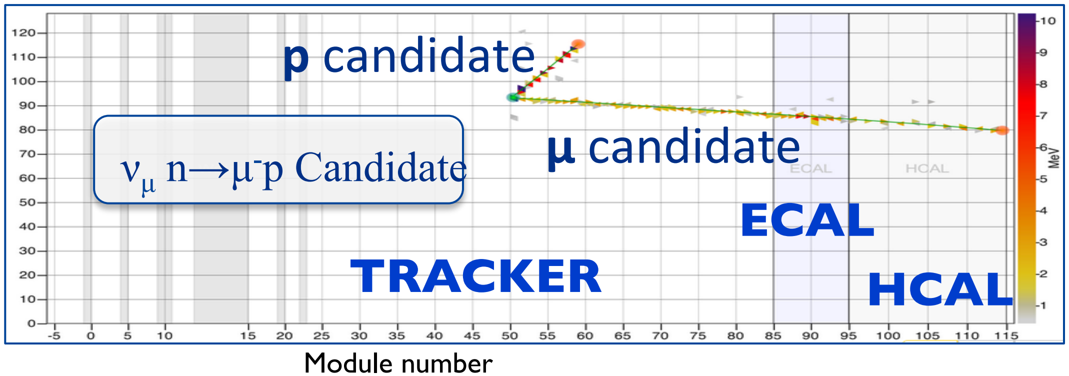
MINERvA Datasets

- Low energy dataset complete
  - Data in both neutrino- and antineutrino-enhanced beams
  - Used to study both signal and background reactions relevant to oscillation experiments
  - And to measure nuclear effects in inclusive and exclusive reactions
  - Unique overlap with DUNE flux
- Medium energy data-taking ongoing
  - Higher statistics yields improve comparisons across nuclei
  - Access to expanded kinematics and nuclear structure functions

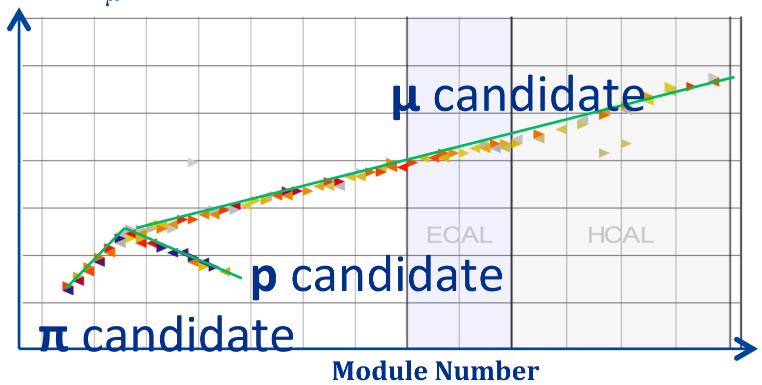


MINERvA Events

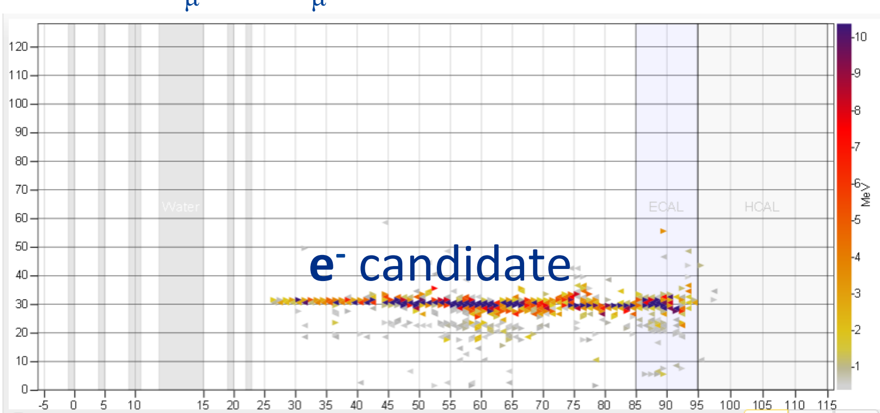
One out of three views shown, color = energy

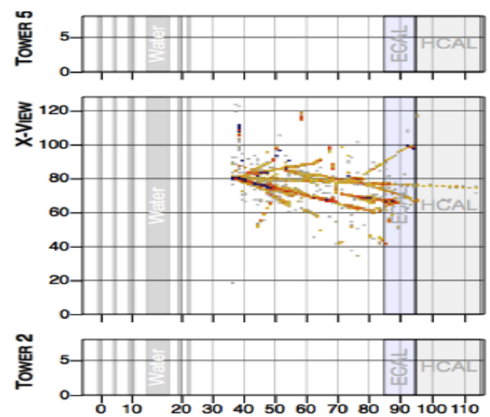


$\nu_\mu\, p \rightarrow \mu^- \Delta^{++},\ \Delta^{++} \rightarrow p\pi^+$ Candidate

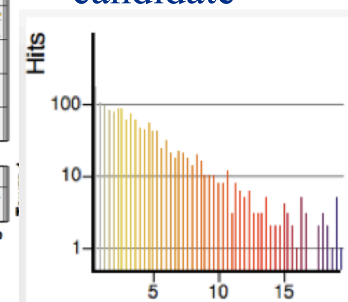


$\nu_\mu\, e^- \rightarrow \nu_\mu\, e^-$ Candidate





Deep Inelastic Scattering candidate



MINERvA Publications (as of June 2017)

Twenty MINERvA Physics Papers so far:

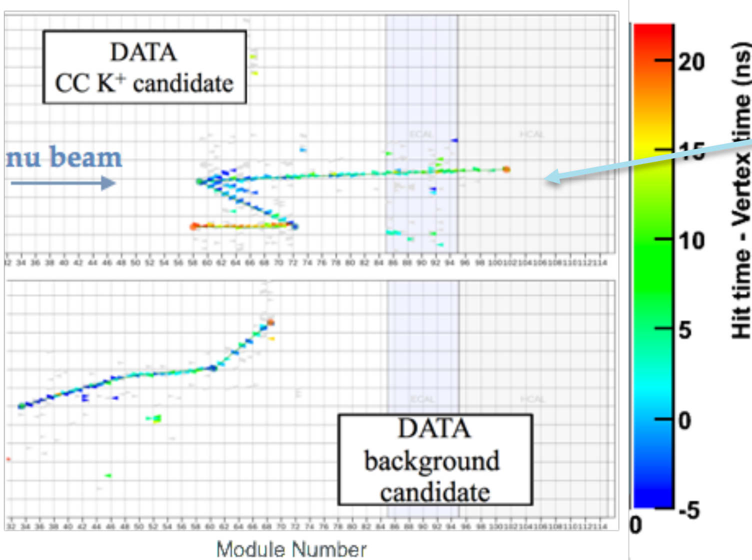
- “Direct Measurement of Nuclear Dependence of Charged Current Quasielastic-like Neutrino Interactions using MINERvA” submitted for publication
- ”Measurement of neutral-current K+ production by neutrinos using MINERvA”, accepted by Phys. Rev. L.
- “Measurement of the antineutrino to neutrino charged-current interaction cross section ratio on carbon” Phys. Rev. D 95, 072009 (2017)
- ”Measurements of the Inclusive Neutrino and Antineutrino Charged Current Cross Sections in MINERvA Using the Low-ν Flux Method”, Phys. Rev. D 94, 112007 (2016)
- “Neutrino Flux Predictions for the NuMI Beam”, Phys. Rev. D 94, 092005 (2016)
- “First evidence of coherent K+ meson production in neutrino-nucleus scattering”, Phys. Rev. Lett. 117, 061802 (2016)
- “Measurement of K+ production in charged-current νμ interactions”, Phys. Rev. D 94 012002 (2016)
- “Cross sections for neutrino and antineutrino induced pion production on hydrocarbon in the few GeV region using MINERvA”, Phys. Rev. D 94, 052005 (2016).
- ”Evidence for diffractive neutral pion production from hydrogen in Neutrino Interactions on hydrocarbon”, Phys. Rev. Lett. 117, 111801 (2016)
- “Measurement of Neutrino Flux using Neutrino-Electron Elastic Scattering”, Phys. Rev. D 93, 112007 (2016)
- “Measurement of Partonic Nuclear Effects in Deep-Inelastic Neutrino Scattering using MINERvA”, Phys. Rev. D 93, 071101 (2016).
- “Identification of nuclear effects in neutrino-carbon interactions at low three-momentum transfer”, Phys. Rev. Lett. 116, 071802 (2016).
- “Measurement of electron neutrino quasielastic and quasielastic-like scattering on hydrocarbon at average Eν of 3.6 GeV”, Phys.Rev. Lett. 116, 081802 (2016).
- “Single neutral pion production by charged-current anti-νμ interactions on hydrocarbon at average Eν of 3.6 GeV”, Phys.Lett. B749 130-136 (2015).
- “Measurement of muon plus proton final states in νμ Interactions on Hydrocarbon at average Eν of 4.2 GeV” Phys. Rev. D91, 071301 (2015).
- “Measurement of Coherent Production of π± in Neutrino and Anti-Neutrino Beams on Carbon from νμ of 1.5 to 20 GeV”, Phys. Rev.Lett. 113, 261802 (2014).
- “Charged Pion Production in ν_μ Interactions on Hydrocarbon at average Eν of 4.0 GeV” , Phys.Rev. D92, 092008 (2015).
- “Measurement of ratios of ν_μ charged-current cross sections on C, Fe, and Pb to CH at neutrino energies 2–20 GeV”, Phys. Rev. Lett. 112, 231801 (2014).
- “Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at Eν ~3.5 GeV”, Phys. Rev. Lett. 111, 022502 (2013).
- “Measurement of Muon Antineutrino Quasi-Elastic Scattering on a Hydrocarbon Target at Eν ~3.5 GeV”, Phys. Rev. Lett. 111, 022501 (2013).

The following slides are 1-slide overviews of each of these

Neutral Current K+ Production

- Neutral current interactions such as :
  - $\nu\, p \rightarrow \nu\, K+\, \Lambda$
  - $\nu\, n \rightarrow \nu\, K+\, \Sigma-$

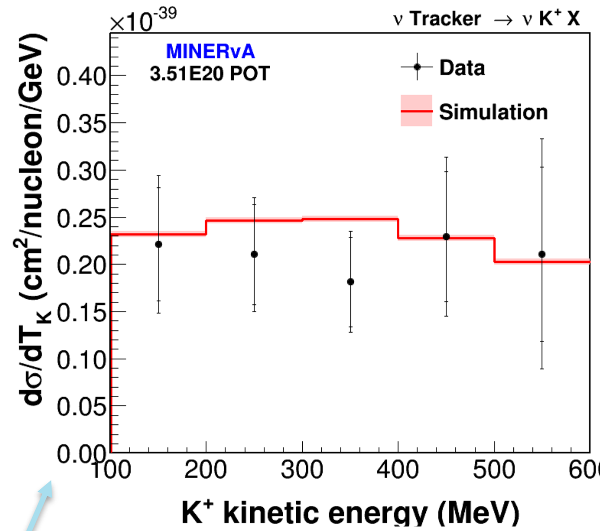
  are backgrounds to Kaon decay searches
- Particularly problematic in Cherenkov detectors, where NC K+ event with no particles above Cherenkov threshold will fake the signal process
- Mismodeled rates for Kaon + nothing would also be a problem in liquid Argon detectors

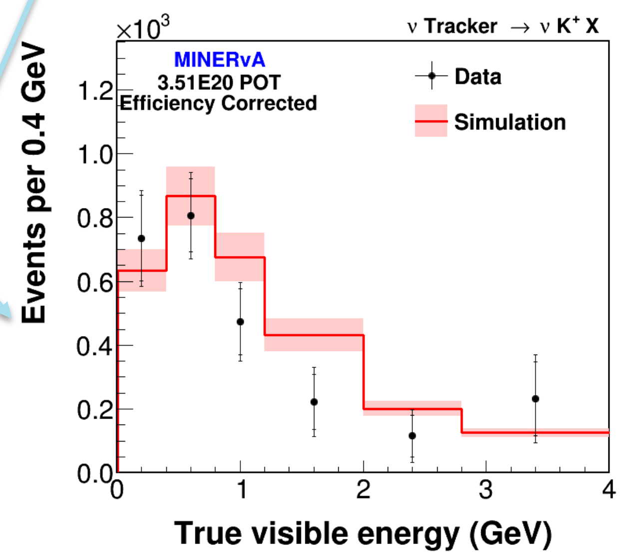


Time separation between K and decay products identifies signal

Kinematic distributions appear well modeled in GENIE

arXiv:1611.0224

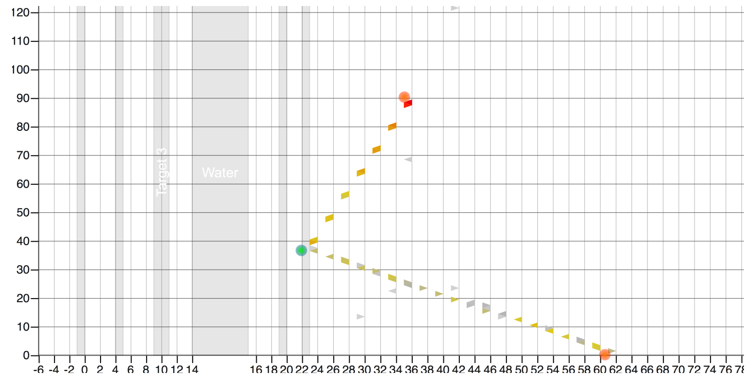




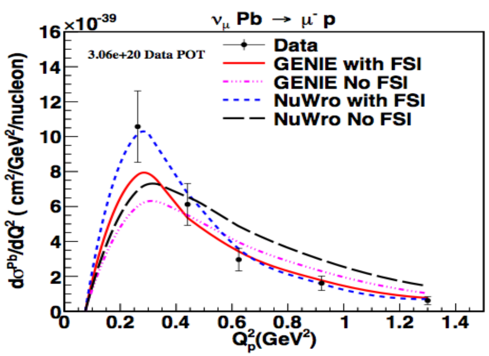
Charged Current Quasi-Elastic on Nuclear Targets

- First CCQE measurements in solid nuclear targets (Carbon, Iron and Lead), aimed at studying Q^2 dependence of nuclear effects
- Q^2 obtained using the kinematics of the protons and very sensitive to final state interactions

$$Q^2 = (M')^2 - M_p^2 + 2M'(T_p + M_p - M')$$



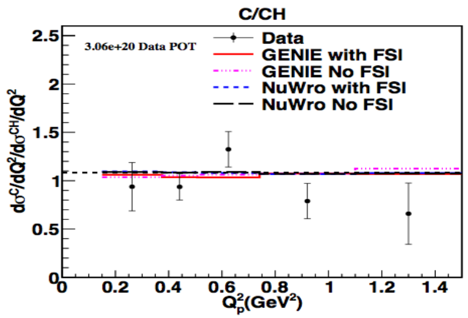
Signal (CCQE-like): Events with one muon, no pions and at least one proton with momentum> 450 MeV/c

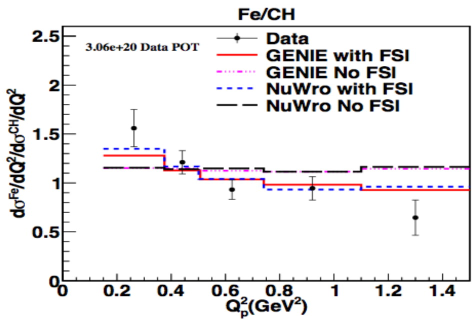


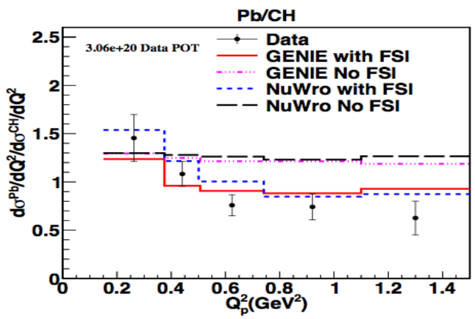
Ratio measurements tell us about nuclear effects such as final state interactions.

The event generators GENIE and NuWro have similar primary interaction models, but different FSI models as a function of A. MINERvA data prefers the NuWro model.

arXiv:1705:03791







Fermilab

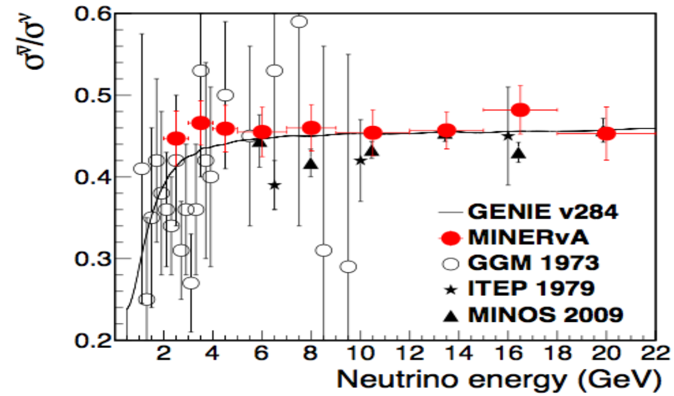
Inclusive Charged Current Cross Section Ratio $\sigma^{\overline{\nu}}/\sigma^{\nu}$

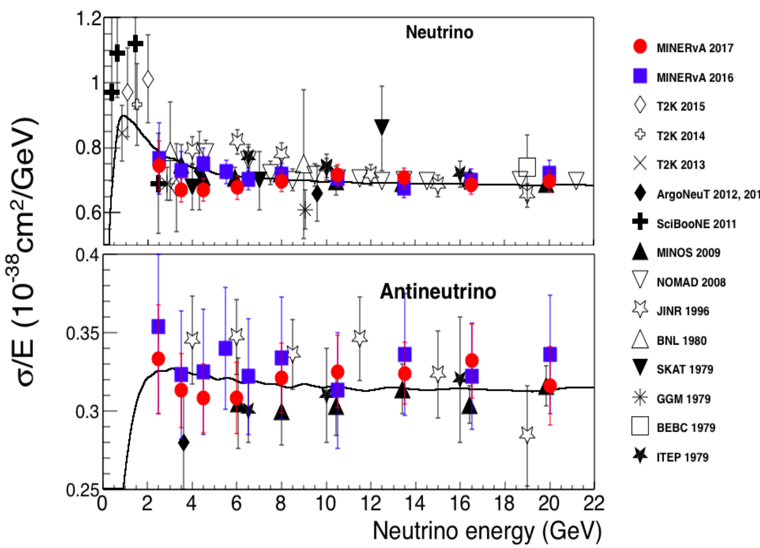
- New precise σ_{ν} / $\sigma_{\bar{\nu}}$ ratio relevant to δ_{CP} measurement

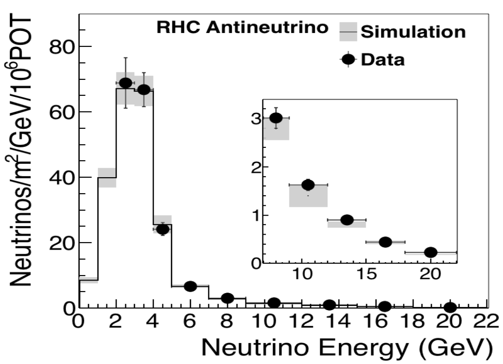
$$\mathcal{A}_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)}$$

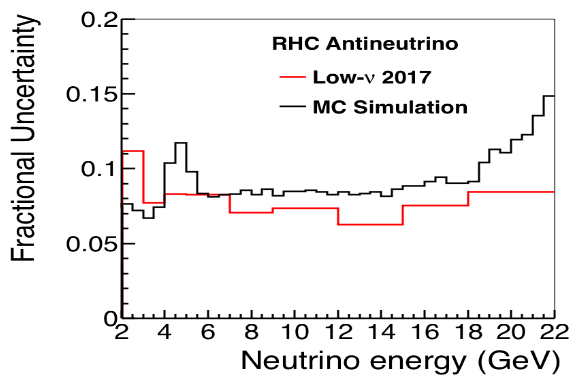
- New method factorizes out model dependence and provides measured model independent rates
- Improved Low-ν flux
  - New method linking high energy low-ν rates (ν vs ν̄)
- Antineutrino cross section result is the most precise to date below 6 GeV (errors dominated by statistical precision)

Phys. Rev. D 95, 072009 (2017)



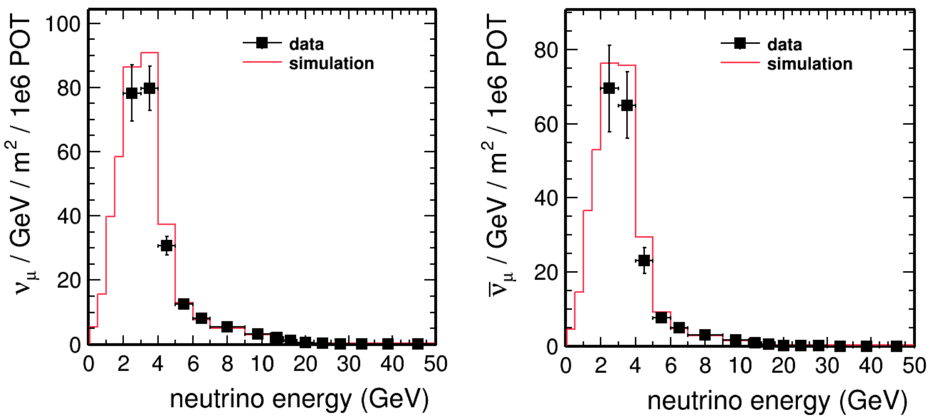


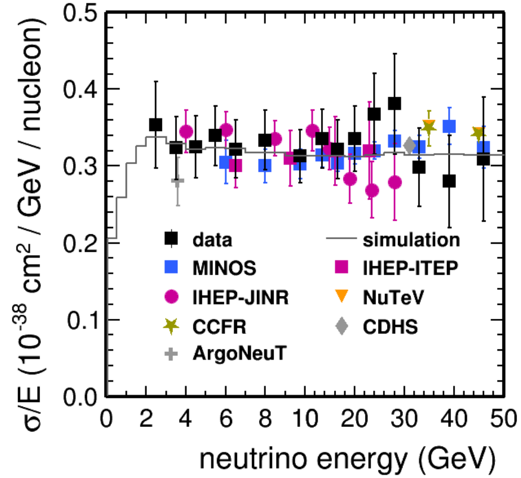




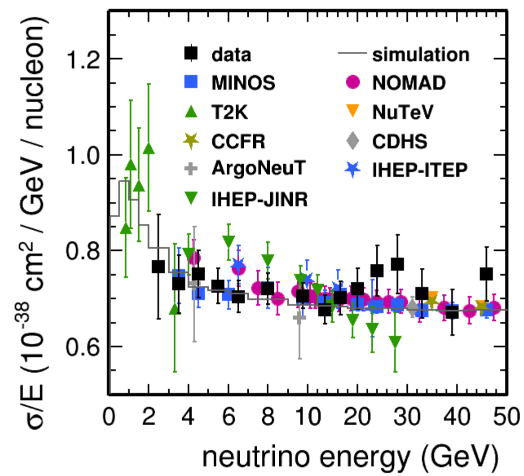
Low-ν Inclusive Cross Sections

Phys. Rev. D 94, 112007 (2016)

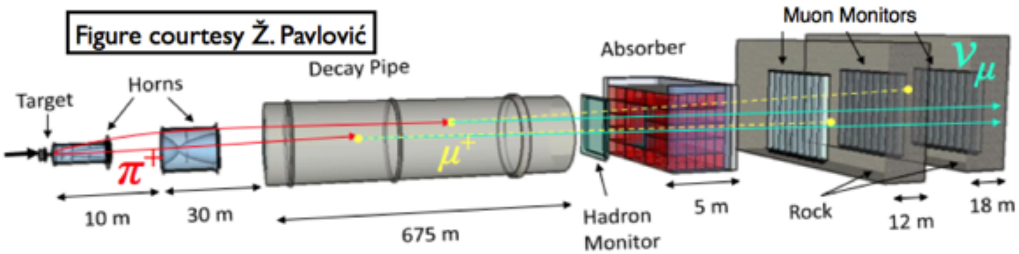




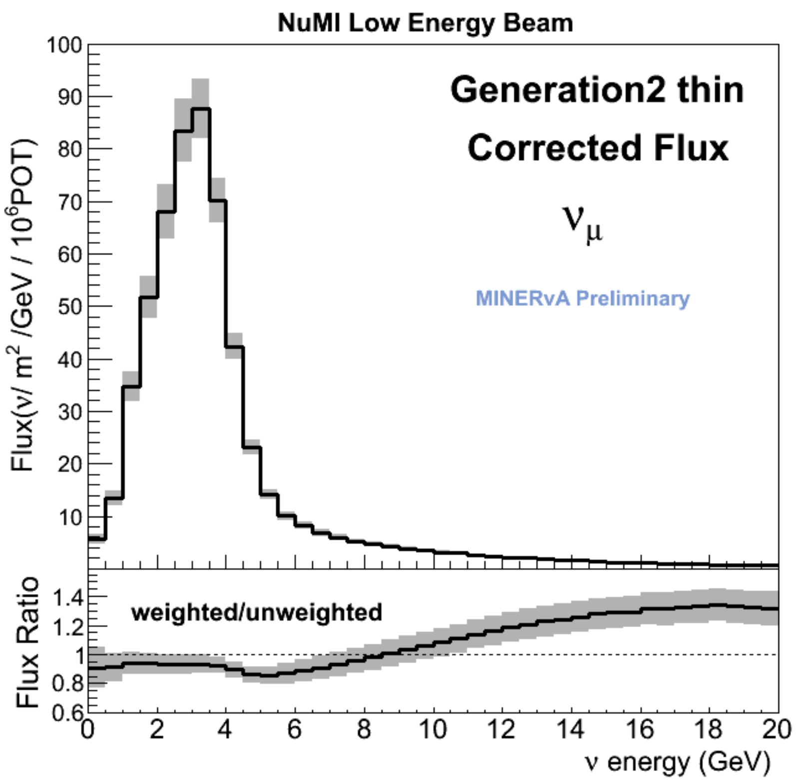
- Low-nu method assumes that the cross section for events with low hadronic energy (ν) is approximately constant with energy
- These events can therefore measure the shape of the flux; absolute flux is extracted using external inclusive cross section data (Nomad used here)
- Flux is then used to measure inclusive cross sections for neutrinos and antineutrinos
- We find the analysis technique is sensitive to multi-nucleon interaction models
  - Systematics grow at low energy
  - Will be a challenge for experiments such as DUNE, who hope to use this method for precise constraints on neutrino flux



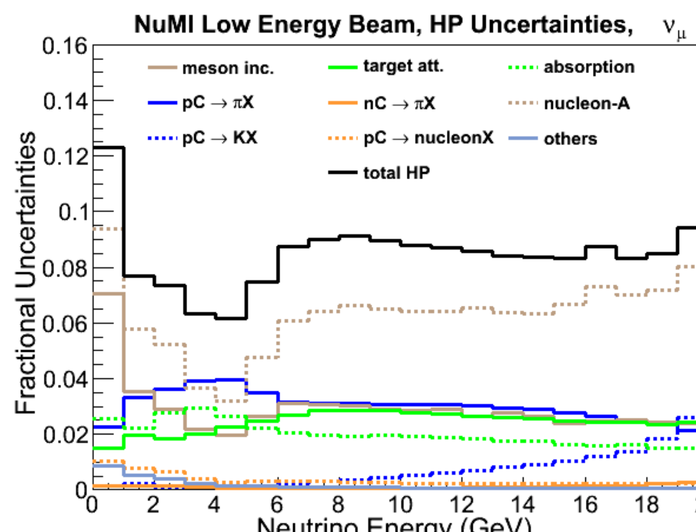
The NuMI Flux



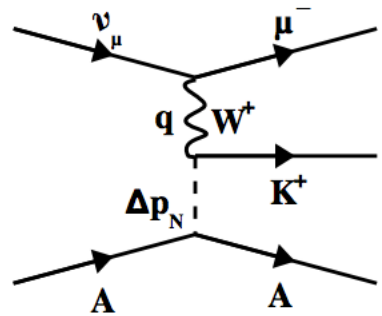
- Neutrino flux prediction based on Geant4 simulation of NuMI
- Simulation is constrained using external hadroproduction data Primarily NA49)
- Achieve ~8% uncertainties in focusing peak
- Further constrained with neutrino +electron scattering (see later slide)

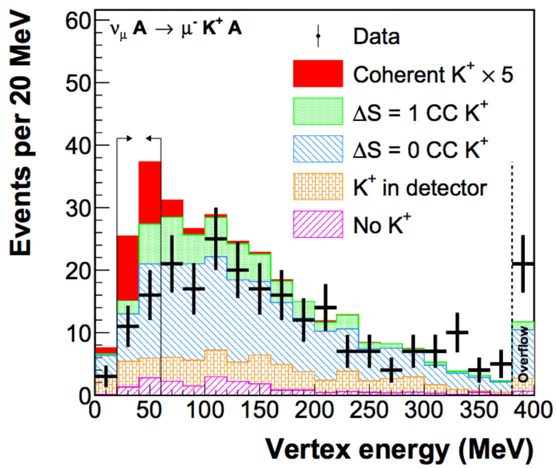


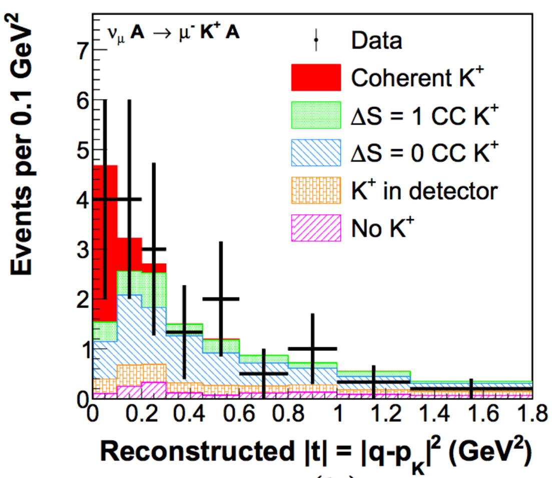
Phys. Rev. D 94, 092005 (2016)



Coherent K+ Production

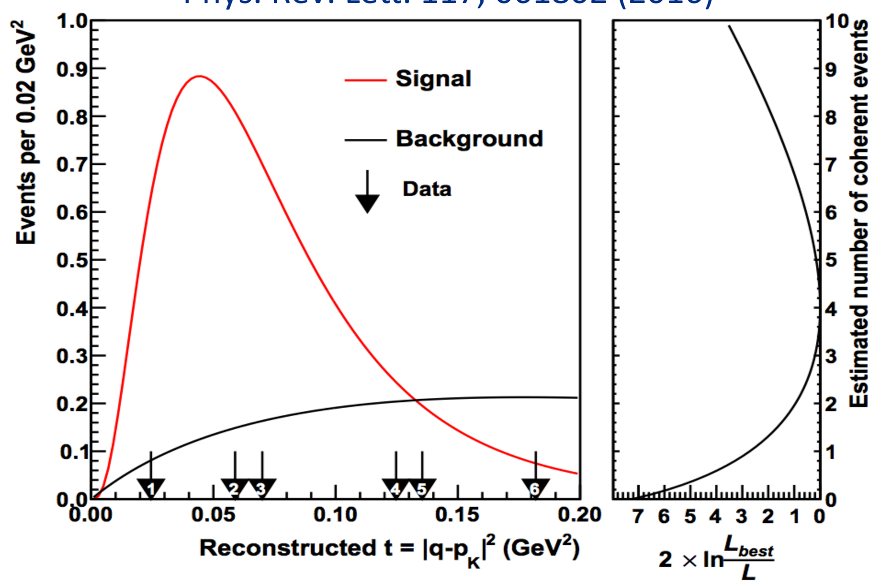






- Very rare process
- Identified via cuts on vertex energy and t, scans to remove π^0 contamination
- We find 6 events in signal region; fit estimates $3.77^{+2.64}_{-1.93}$ signal events; null hypothesis ruled out at 3σ

Phys. Rev. Lett. 117, 061802 (2016)

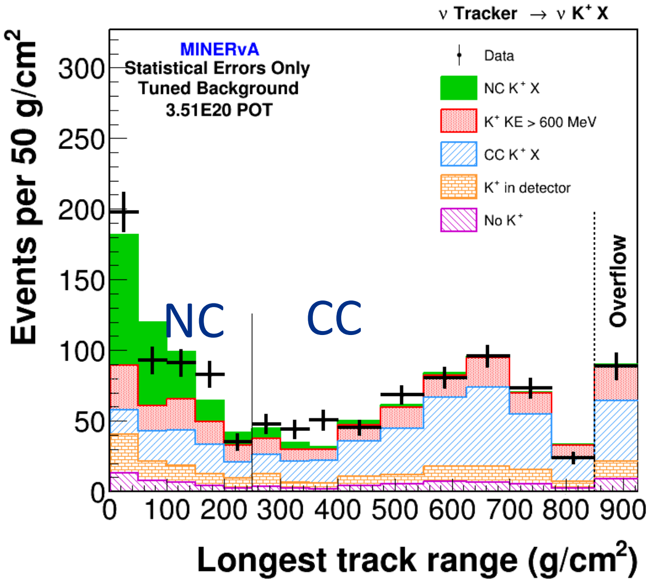


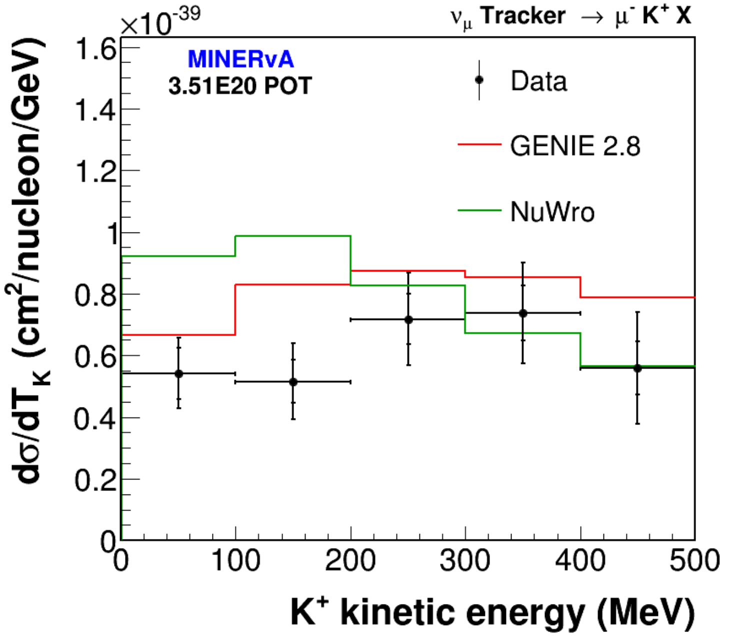
Charged Current K+ Production

- Complimentary analysis to Neutral Current K+ production
- Both processes are very sensitive probes of Kaon FSI, which is critical to model for proton decay searches
- Neutral current and charged current processes separated via range of longest reconstructed track

Total rate overestimated by both GENIE and NuWro. MINERvA sees significant deficit of low energy kaons compared to NuWro prediction.

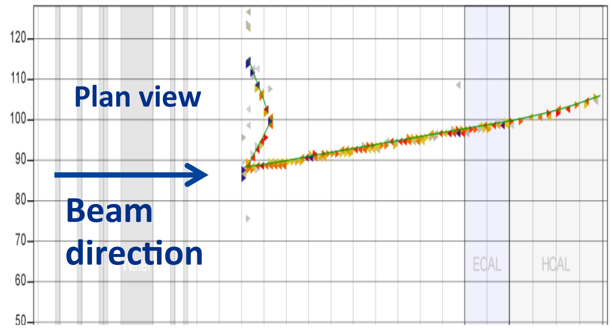
Phys. Rev. D 94 012002 (2016)





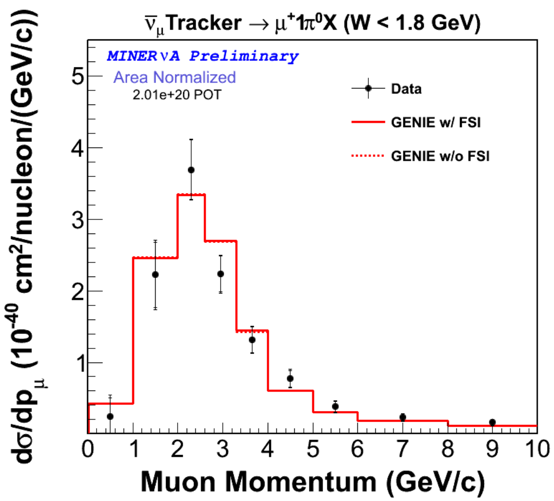
CC Pion Production: Muon Variables

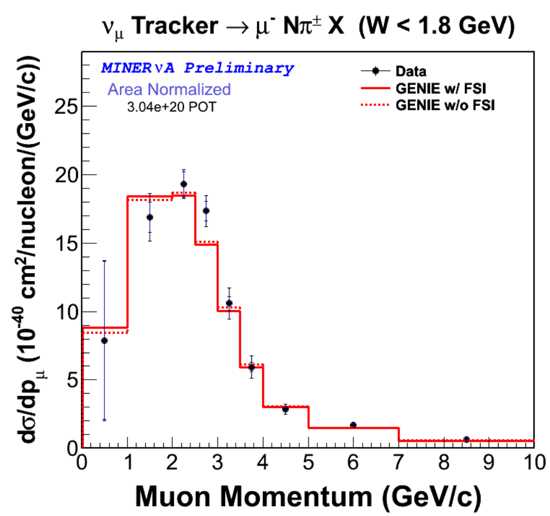
Phys. Rev. D 94, 052005 (2016).



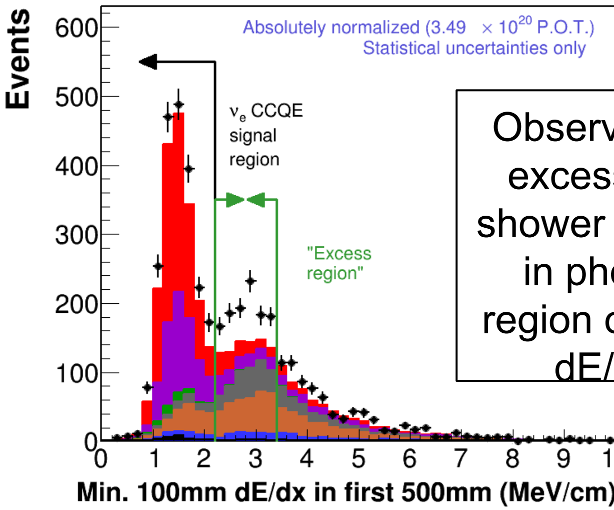
Shape of charged current pion production cross section versus **muon kinematics** is independent of FSI model.

GENIE agrees well with MINERvA's data here, indicating that the disagreement in pion variables (see later slide) is likely due to problems with FSI models

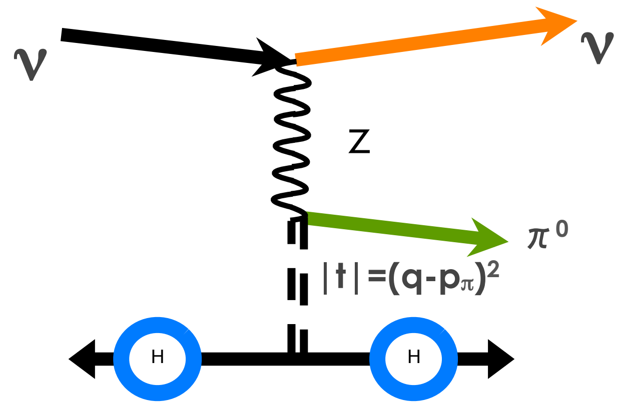




Neutral Current Diffraction π^0 Production

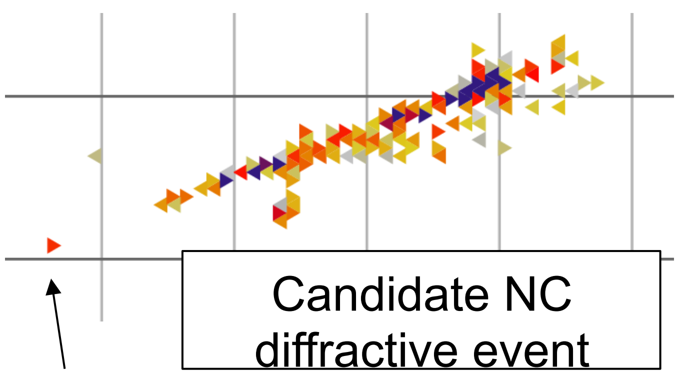


Observed as excess EM shower events in photon region of front dE/dx



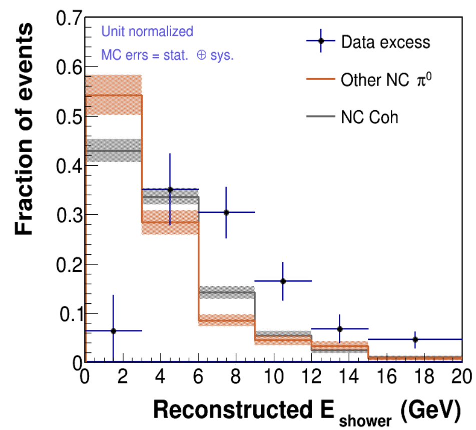
Analogous to NC coherent production. Potential background for ν_e appearance. Not in default generator models.

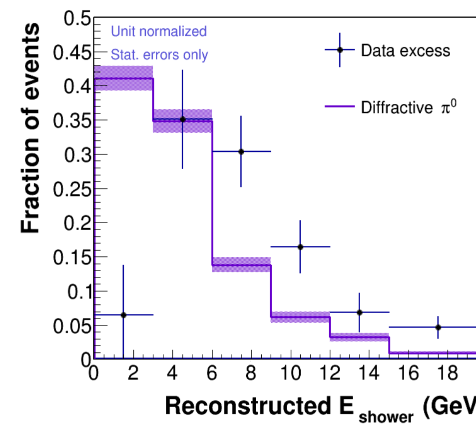
", Phys. Rev. Lett. 117, 111801 (2016)



Candidate NC diffractive event

Probable recoil from proton



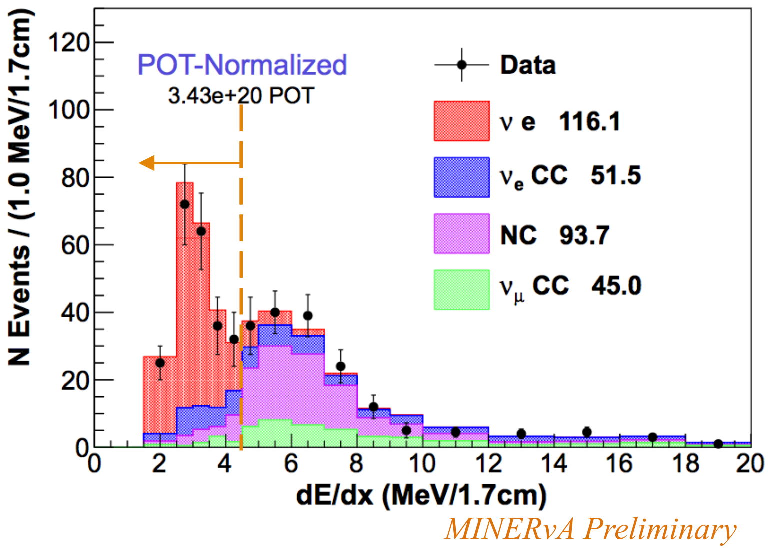


Observed energy behavior is very different from any other NC π^0 production models

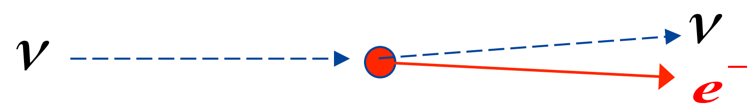
Neutrino-Electron Scattering

Can we isolate a sample of these well-predicted events to directly measure neutrino flux?

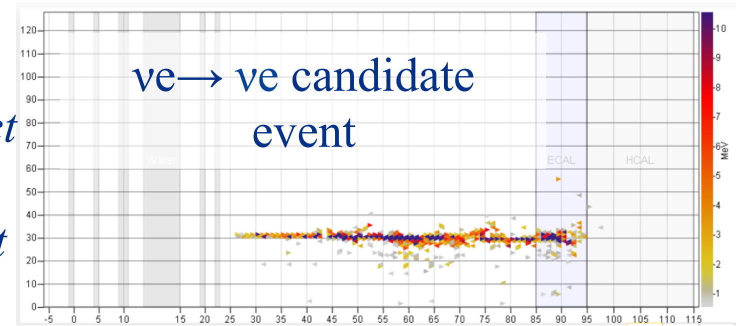
dE/dx<4.5MeV/1.7cm



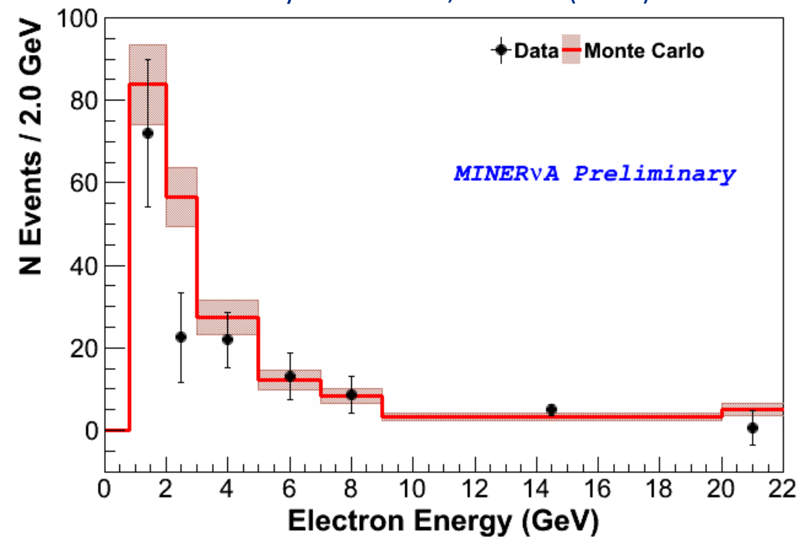
Very forward single electron final state



Use early ionization to reject photons and direction to reject interactions on nucleons



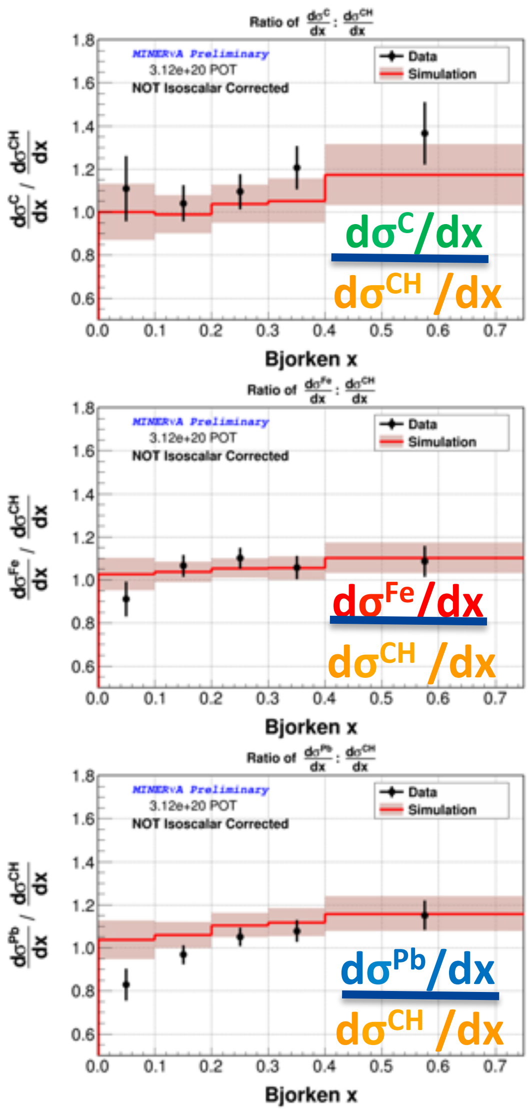
Phys. Rev. D 93, 112007 (2016)



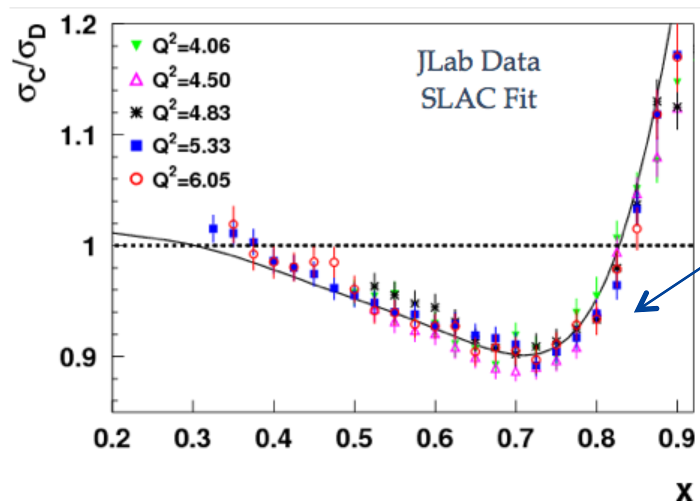
Measurement in LE NuMI beam reduces flux uncertainty from ~8% to ~7% in focusing peak

Analysis underway in NOvA era beam, with much improved statistics

Deep Inelastic Scattering



Seely, J. et al. Phys.Rev.Lett. 103 (2009) 202301 arXiv:0904.4448



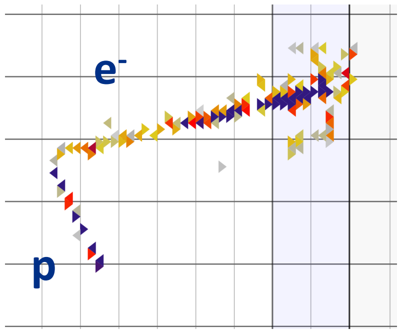
EMC Effect: dip in heavy/ light nucleus cross section ratio at moderate x

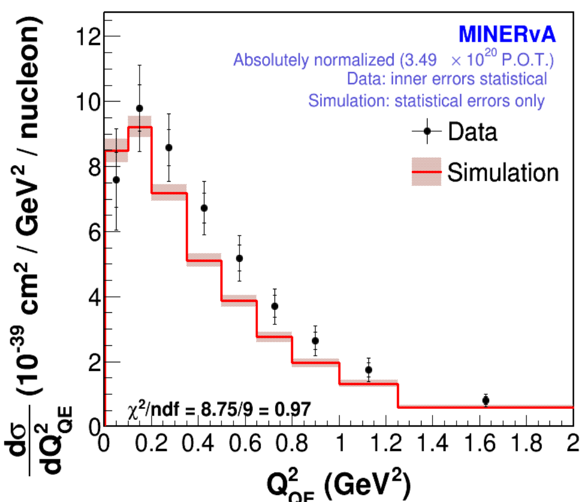
MINERvA is the first experiment to look for the "EMC Effect" in neutrino scattering

No evidence of discrepancy with model (which does not include EMC effect). Currently statistically limited. Much higher stats analysis underway

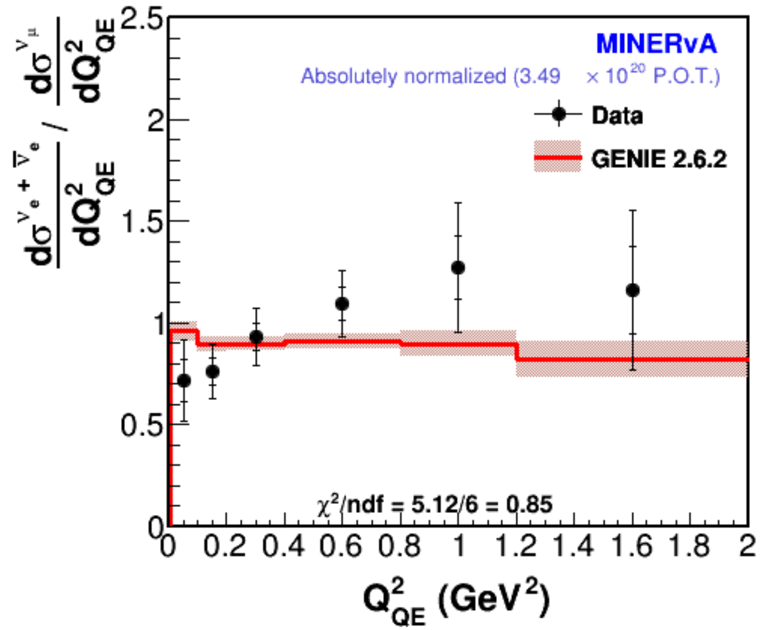
CCQE: Electron Neutrinos

Electron neutrino CCQE is a key oscillation signal, but has not cross section data; can we trust lepton universality in complex nuclei?





Measured cross sections consistent with GENIE model (assumes charged lepton mass only difference between XS) at 1σ (~15-20% uncertainties)



ν_e/ν_μ difference not significant (~1σ). Good enough for current expts. but shape may need further investigation for future high-precision oscillation results

Phys.Rev. Lett. 116, 081802 (2016).

Fermilab

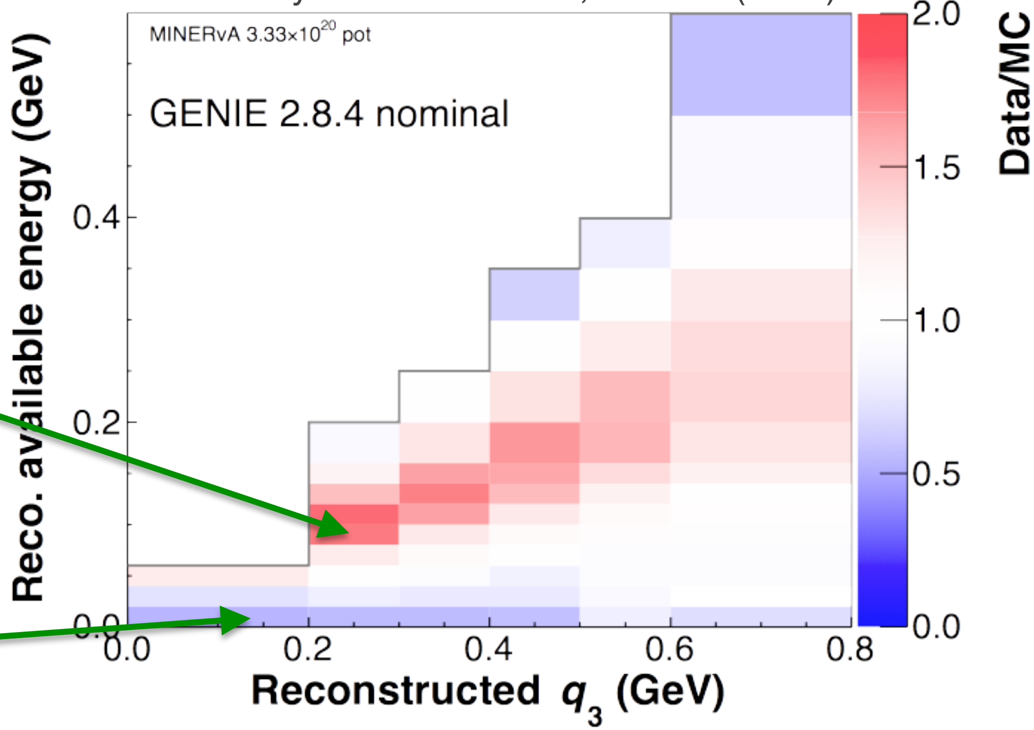
Inclusive Charged Current (Low Recoil)

- Cross section measured in two variables that show how the neutrino's energy is split between the outgoing muon and outgoing hadrons.
- Oscillation experiments depend on modeling this split correctly!

Data higher than model in region where neutrino scatters off two nucleons

Data lower than model in region where neutrino sees combined effect of the nucleus as a whole

Phys. Rev. Lett. 116, 071802 (2016)

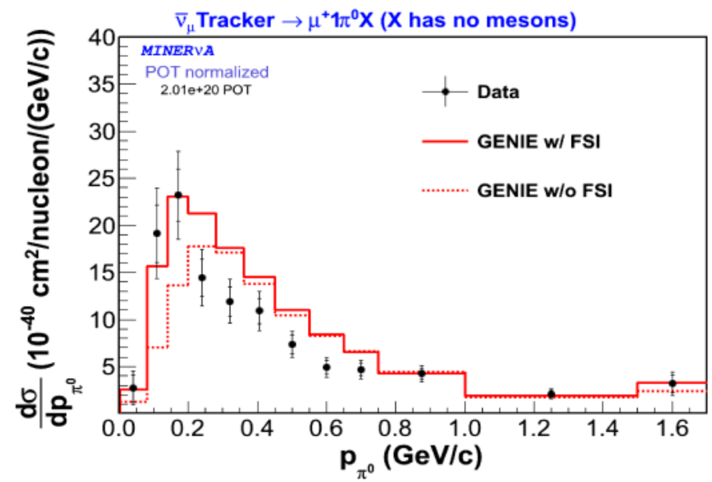


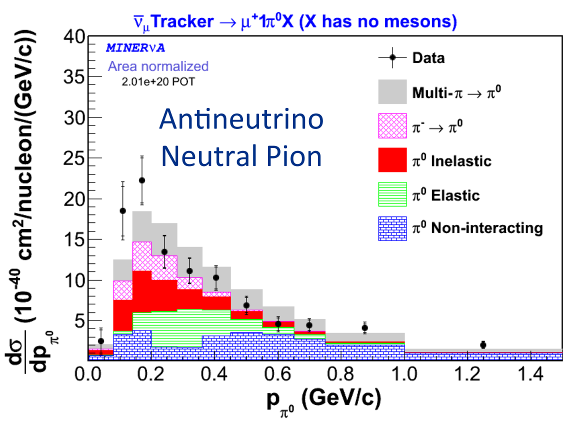
Strong evidence for two nuclear effects not in our standard prediction

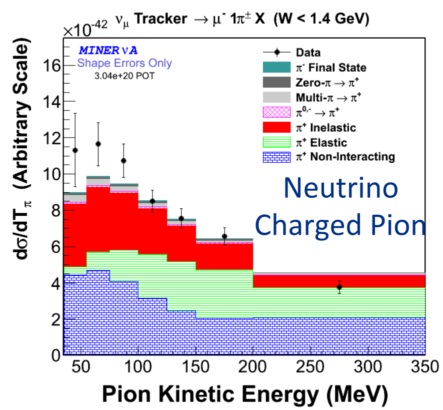
Neutral Pion Production

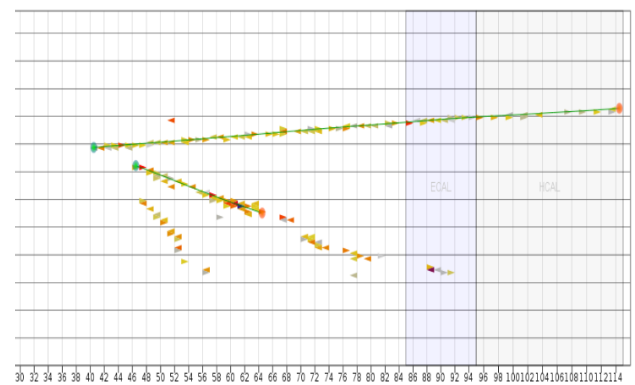
Do we correctly model nuclear rescattering – complementary to charged pion production

Antineutrino cross section indicates good model agreement in kinematic regions where Final State Interactions (FSI) are minimal, but tension with models in FSI-dominated regions







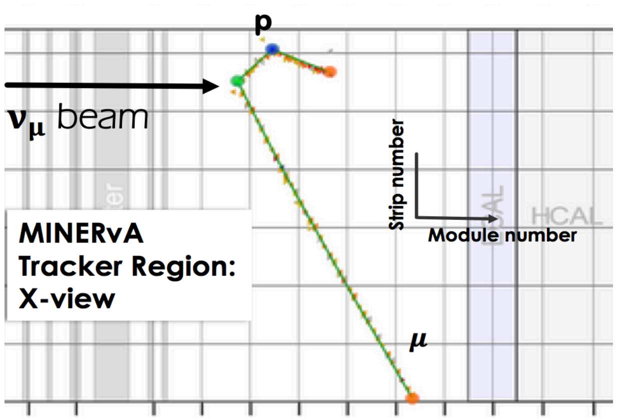


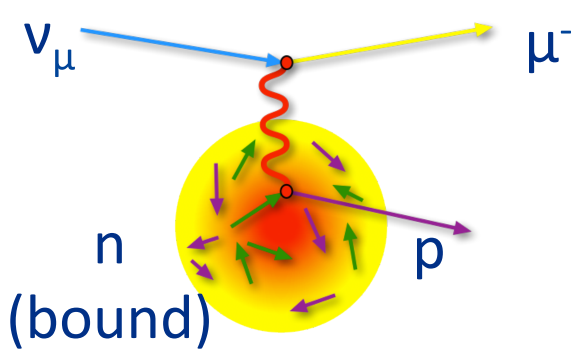
Phys.Lett. B749 130-136 (2015).

MINERvA's pion measurements are powerful discriminators of FSI models

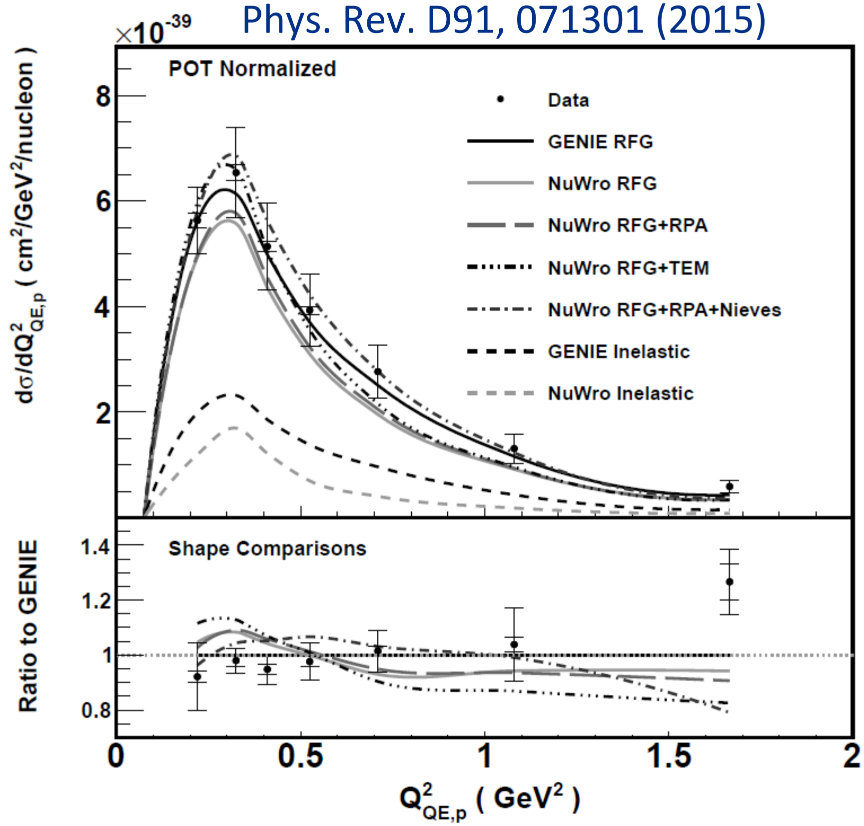
CCQE: Proton Kinematics

Momentum transfer (Q^2) can be measured from proton energy in CCQE events





Phys. Rev. D91, 071301 (2015)

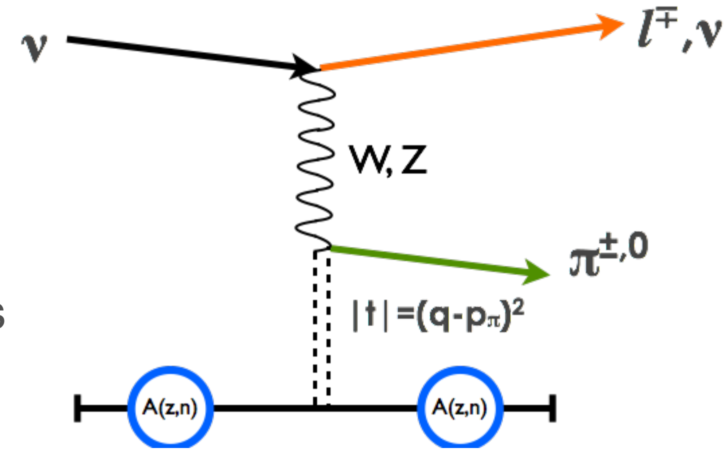


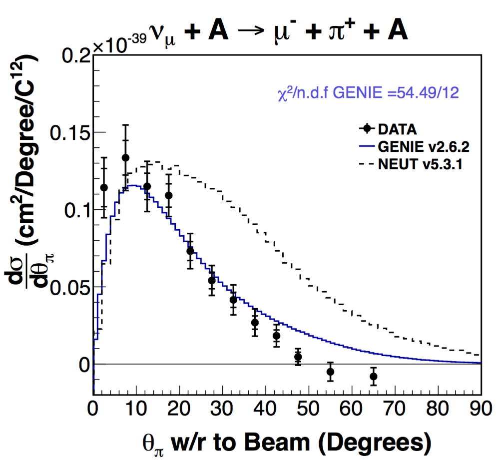
Data agrees well with models without multinucleon effects, in contrast to muon measurement (see later slides)

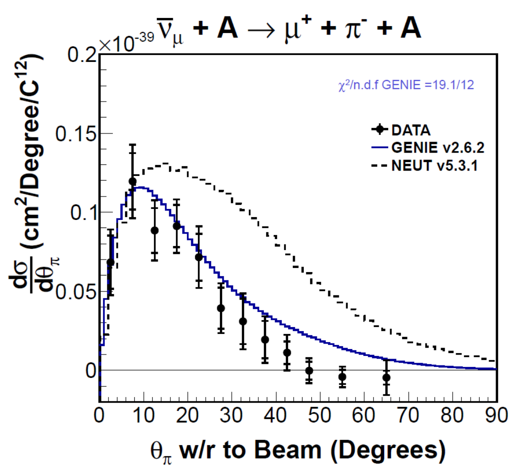
Coherent Pion Production

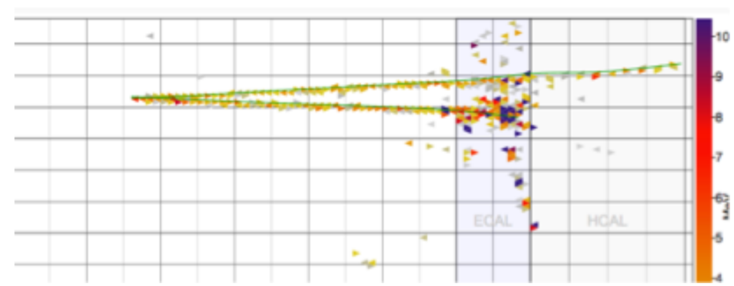
Can we resolve experimental puzzles on rate for this process?

- This low multiplicity process is a troublesome background for oscillation experiments and previous low energy data is confusing
- Model independent selection and high statistics allows test of pion kinematics
- 1628 (770) coherent neutrino (antineutrino) events





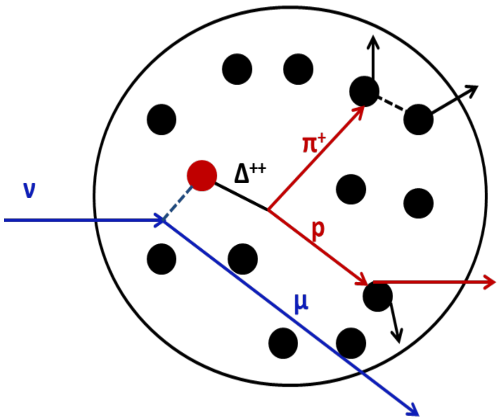




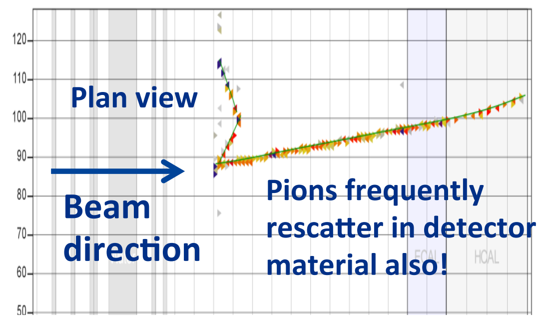
Phys. Rev.Lett. 113, 261802 (2014).

Current generators don't model process well at LBNF energies

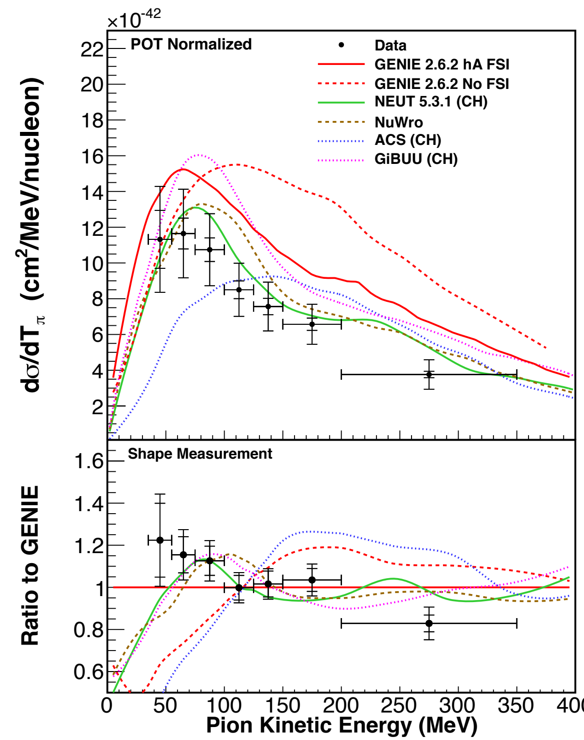
CC Pion Production: Pion Variables



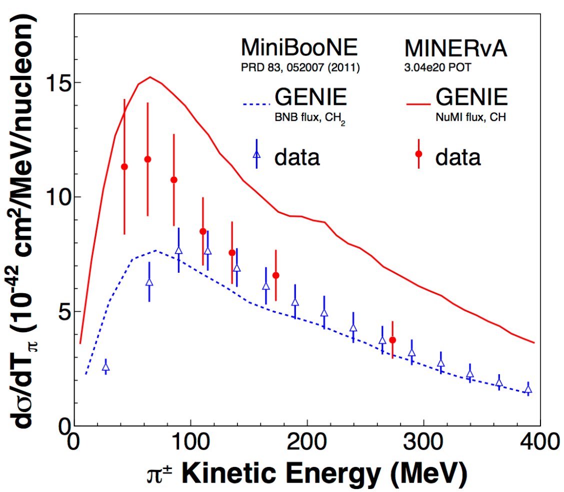
Do we correctly model nuclear rescattering?



MINERvA Data strongly prefers models with FSI; indicates GENIE significantly overpredicts pion production



Phys.Rev. D92, 092008 (2015).



MiniBooNE's measurement of same reaction sees harder momenta, more events and suggest less FSI.

There is significant tension between the experiments.

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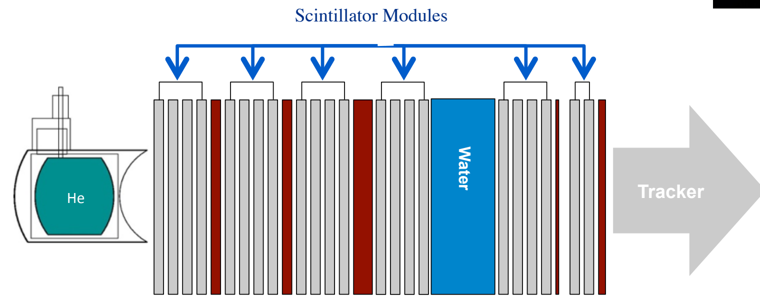
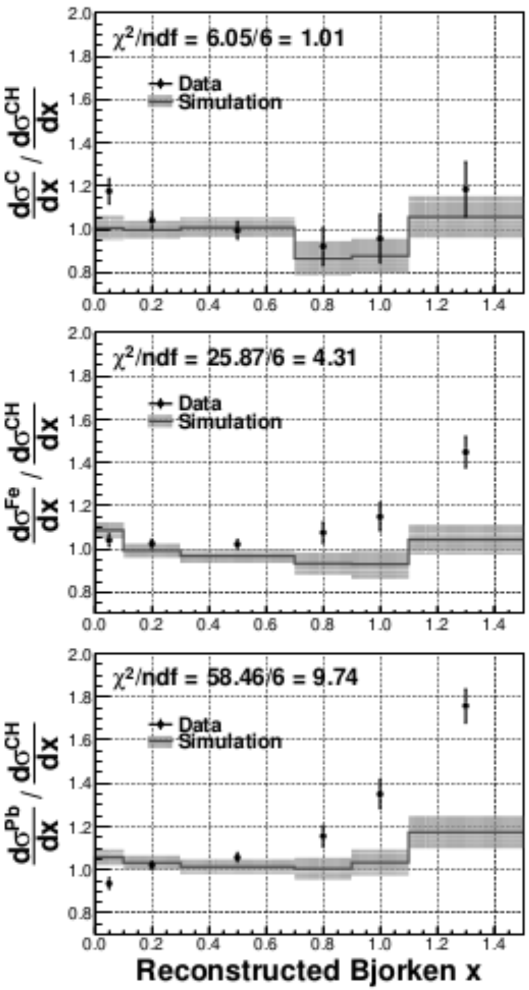
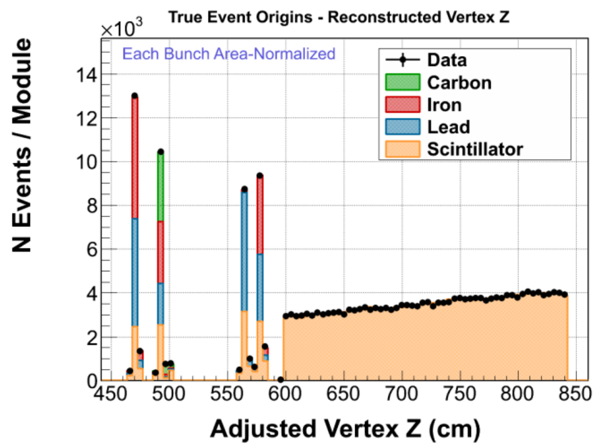
CC Inclusive on Nuclear Targets

How are CC reactions modified by nucleus?



Phys. Rev. Lett. 112, 231801 (2014)





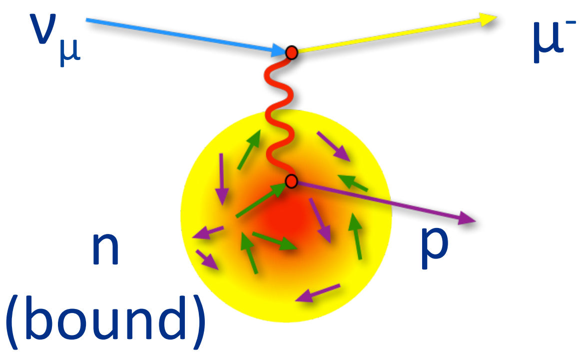
Targets are passive and there is contamination from nearby scintillator.

Use events in the tracker modules to estimate and subtract contamination from scintillator events.

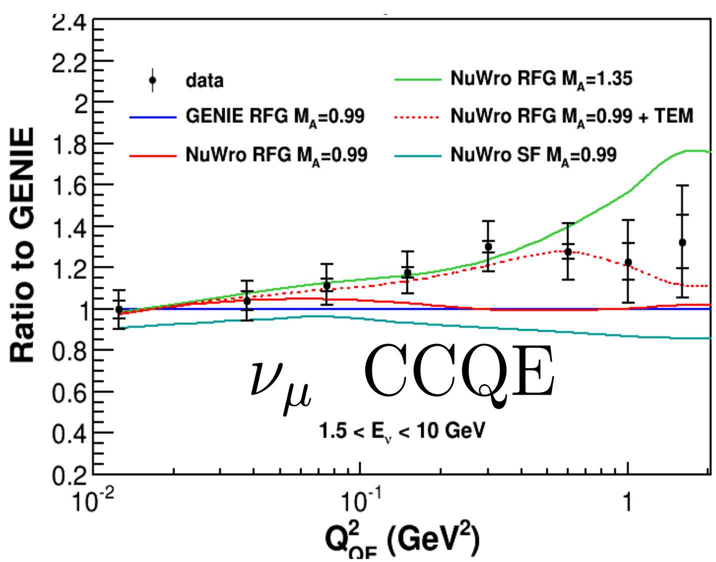
1. *At low x*, we observe a *deficit* that increases with the size of the nucleus.
2. *At high x*, we observe an *excess* that increases with the size of the nucleus.

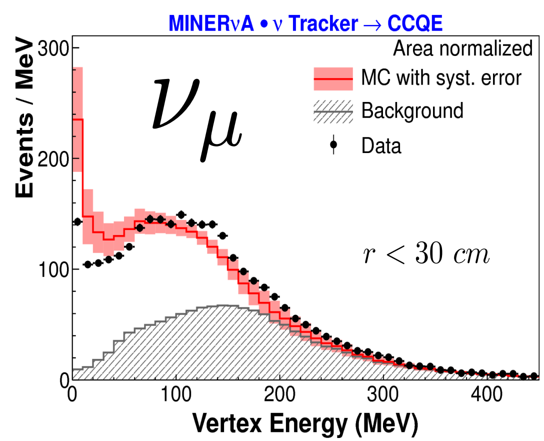
These effects are not reproduced by current neutrino interaction models.

CCQE: Muon measurement (Neutrinos)



- CCQE (not CCQE-like) signal definition
- Measurement of Q^2 measured via muon kinematics prefers transverse enhancement model
- Energy observed around vertex consistent with extra unmodeled protons





Energy near vertex prefers with adding an extra proton to 25±9% of events, also consistent with a multinucleon hypothesis

Phys Rev. Lett. 111, 002052 (2013), updated to 2015 flux

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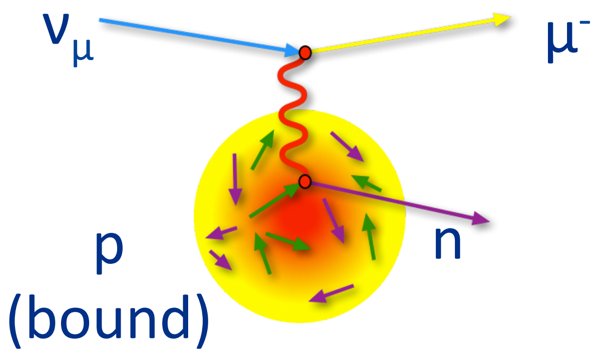
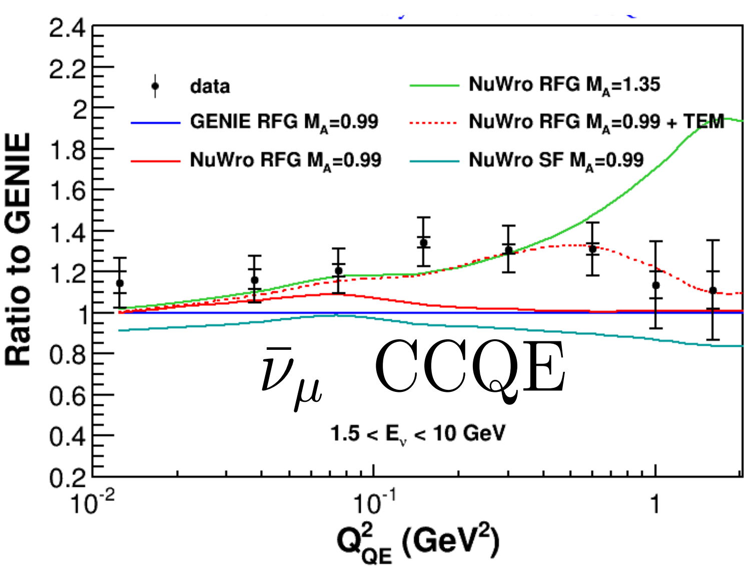
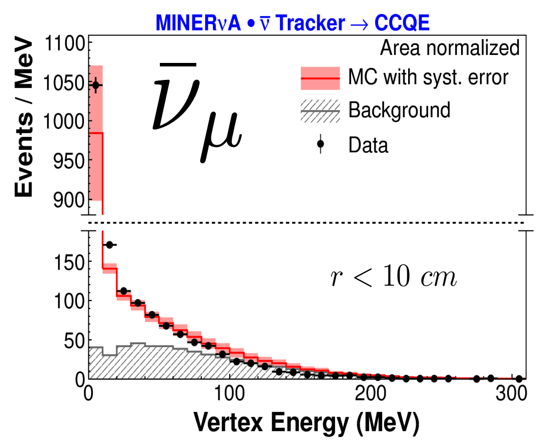
CCQE: Muon measurement (Antineutrinos)



- CCQE (not CCQE-like) signal definition
- Measurement of Q^2 measured via muon kinematics prefers Transverse Enhancement model that attempts to account for multinucleon effects
- Energy observed around vertex consistent with extra unmodeled protons



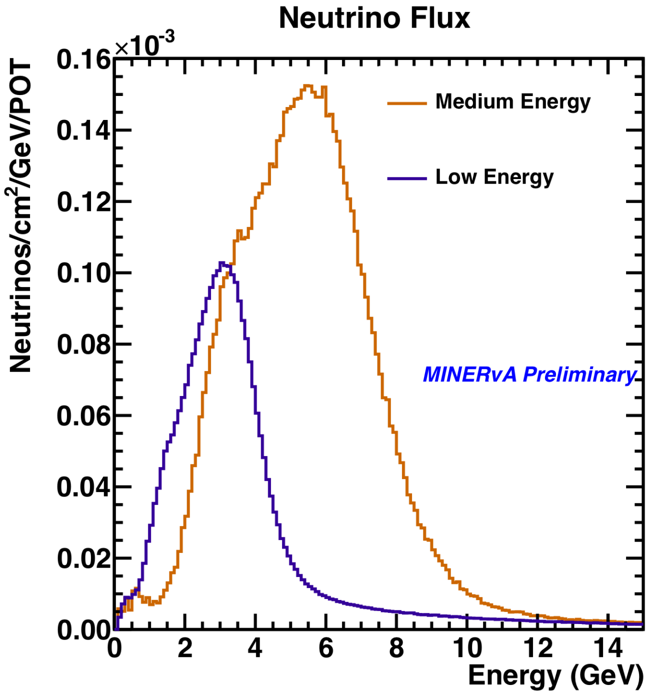


For antineutrinos, energy around vertex consistent with NO extra unmodeled protons (expected if multinucleon interactions are primarily on np pairs)

Phys Rev. Lett. 111, 002051 (2013), updated to 2015 flux

MINERvA Future Plans

- Finishing up last low-energy results:
  - More studies of Quasi-Elastic Interactions
    - Double Differential cross sections, improved reconstruction
    - Cross Section Ratios: Pb/CH, Fe/CH
- Currently taking Medium Energy data
  - Event rates much higher
  - Have already accumulated 3x the exposure of LE dataset in neutrino mode; expect similar antineutrino exposure (12e20)
  - Will be able to probe nuclear effects for several channels, especially DIS
- **Results should continue to improve model descriptions used by both theory and oscillation experiments**



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From the MINERvA Collaboration…

Thank You!